Chapter 5

Fade and Non-Fade Durations and Phase Spreads

5.1 Background

It is important to know the length of time an LMSS channel is available and unavailable without interruption for optimally designing communication systems which handle coded messages over defined bandwidths. Receivers designed by communication engineers may, for example, be equipped with a digital soft-decision modem and a powerful foward error correcting code implemented with a convolution coder and Viterbi decoder. To optimally design such receivers, which have only two states, good or bad, a knowledge is required of the statistics associated with durations of fades which fall below and above defined attenuation thresholds. In order to implement proper designs of demodulators for coded data, it is also important to have knowledge of the phase fluctuations during conditions of fading arising from multipath and shadowing.

Fade duration results at L-Band were derived by the authors from measurements in central Maryland [Goldhirsh and Vogel, 1989] and South-Eastern Australia [Hase et al., 1991]. The former measurement campaign was implemented employing a helicopter as the transmitter platform, and the latter, the Japanese ETS-V [Vogel et al., 1991]. During the latter campaign, phase fluctuations were also measured and associated statistics described

[Hase et al., 1991].

5.2 Experimental Aspects

Measurements performed in south-eastern Australia employed left-hand circularly polarized cw transmissions radiated from the Japanese ETS-V satellite at a frequency of 1545.15 MHz. The in- and quadrature-phase detector voltages (noise bandwidth = 1 kHz) as well as the output from a power detector with pre-detection bandwidth of 200 Hz were recorded at a 1 kHz rate. The receiver antenna consisted of a crossed drooping dipole antenna having a 4 dB gain, an azimuthally omni-directional radiation pattern, and a relatively flat elevation pattern over the beamwidth 15° to 75° (Table 3.3).

Fade duration results were derived by analyzing the average of two consecutive 1 millisecond samples. All fade and non-fade durations were expressed in units of traveled distance (m) for which the fades were continuously exceeded or were less than thresholds ranging from 1 to 8 dB. The "distance durations" may be converted to "time durations" by dividing the former by the speed (which was nominally 25 m/s).

The phase data were extracted from the quadrature detected signals where the low frequency components, due primarily to oscillator drift and Doppler shift changes, were rejected by digital filtering. The phase shifts measured were therefore caused by roadside obstacles.

The following emphasizes the Australian data base (elevation to satellite = 51°). Fade durations have also been examined for the central Maryland region [Goldhirsh and Vogel, 1989] and these results show a slight dependence on elevation angle.

5.3 Cumulative Distributions of Fade Durations

The fade durations were with good accuracy observed to follow the lognormal distribution

dd ≥ .02 m

$$P(\mathrm{FD} > \mathrm{dd} \mid \mathrm{A} > A_q) = \frac{1}{2}\left\{1 - \mathrm{erf}\left[\frac{(\ln \mathrm{dd} - \ln \alpha)}{\sqrt{2}\,\sigma}\right]\right\} \tag{5.1}$$

Table 5.1: Best fit exponential cumulative fade distributions parameters u and v from form (5.3) derived from measurements on roads exhibiting "extreme" and "moderate" shadowing for a path elevation angle of 51°.

Road Type	u	v	rms (dB)	Fade Range (dB)
Moderate	17.57	0.2184	0.1	$2-13$
Extreme	95.78	0.1951	0.3	$2-15$

where $P(FD > dd \mid A > A_q)$ represents the probability that the distance fade duration FD exceeds the duration distance dd under the condition that the attenuation A exceeds A_q. Also, erf is the error function, σ is the standard deviation of $\ln dd$, and $\ln\alpha$ represents the mean value of $\ln dd$. The left hand expression (5.1) was estimated by computing the percentage number of "duration events" which exceed dd relative to the total number of events for which $A > A_q$. An event of duration distance dd occurs whenever the fade crosses a threshold level A_q and persists "above that level" for the driving distance dd. A desired expression is the joint probability that FD exceeds dd and A exceeds A_q. This is given by

$$P(FD > dd, A > A_q) = P(FD > dd \mid A > A_q)\, P(A > A_q) \tag{5.2}$$

where $P(A > A_q)$ is the absolute probability that the fade exceeds the threshold A_q and is given by cumulative fade distributions described in Figure 5.1 for road-types whose degrees of shadowing are classified as "extreme" and "moderate". The "extreme" condition corresponds to measurements along a road having a continuum of overhanging tree canopies where almost persistent shadowing occurred. This condition is generally not encountered and is presented here as a "worst case" scenario. The "moderate" condition corresponds to measurements in which there were 50% to 75% of optical shadowing. This distribution was used as part of the overall data base employed to validate the ERS model (Section 3.4). These distributions are described by the "best fit" exponential

$$P(A > A_q) = u \exp(-vA_q) \tag{5.3}$$

where P is the percentage of the distance driven over which the fade A_q (in dB) is exceeded. The parameters u and v are tabulated in Table 5.1 along with the rms deviations of the measured distributions relative to the best fit curves.

For the case in which there was a 5 dB fade threshold, fade duration measurements executed on three roads (2 moderate and 1 extreme) exhibited values of α and σ which were

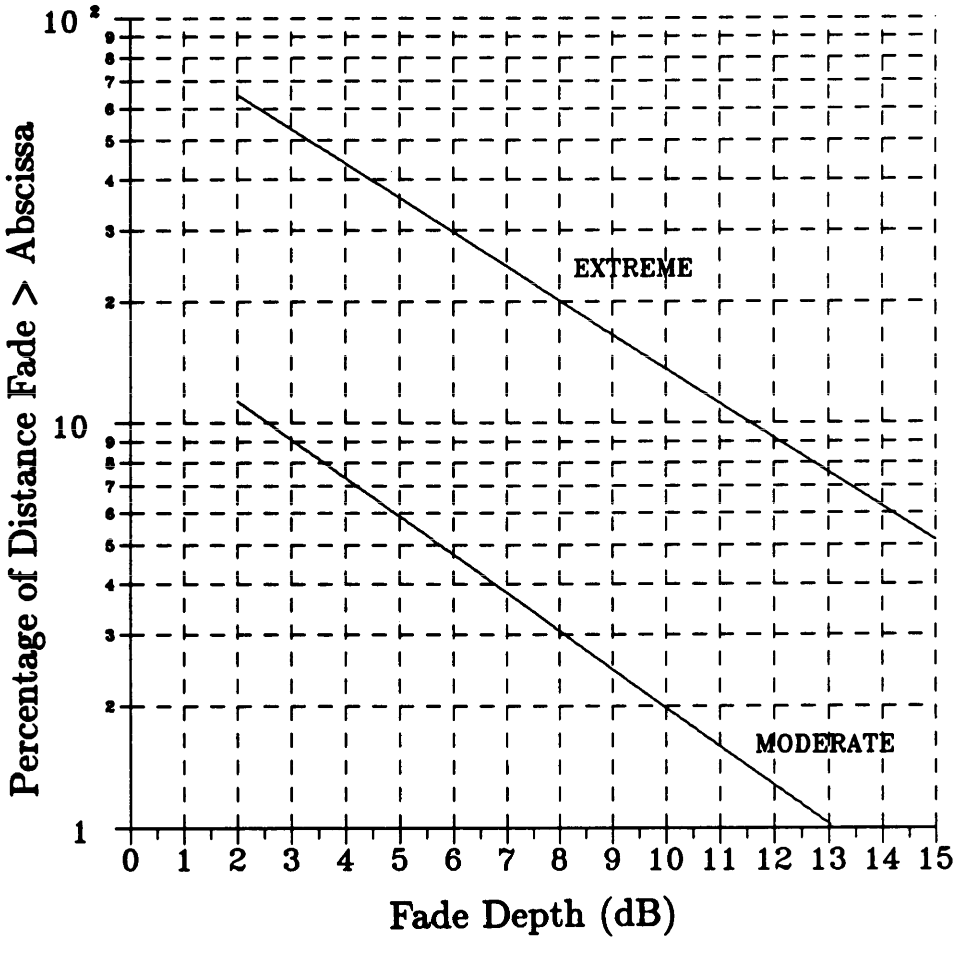

Figure 5.1: Best fit exponential fade distributions of the form (5.3) derived from measurements in South-Eastern Australia along road-types classified as "moderate" and "extreme". Measurements were made at a path elevation of 51°.

Table 5.2: RMS deviations relative to log-normal fit ($\alpha = 0.22$, $\sigma = 1.215$) of cumulative distributions of fade durations (threshold of 5 dB) for various runs exhbiting moderate and extreme shadowing [Equation (5.1)].

Shadowing Level	% RMS Deviation	Distance (km)
Moderate (Run 1)	16.4	33.0
Moderate (Run 2)	18.0	8.1
Extreme	13.6	2.4

nearly coincident for the individual runs. The resultant "best fit" regression values are given by

$$\alpha = 0.22 \tag{5.4}$$

$$\sigma = 1.215 \tag{5.5}$$

As may be noted from Table 5.2, the measured fade durations for the various runs showed an overall rms deviation of less than 20% relative to the those derived employing the best-fit log normal distribution shown plotted in Figure 5.2. For engineering convenience, the lognormal distribution is plotted on logarithmic scales since the percentage values are easier to read.

The fact that a single set of values of α and σ may be applied to the "moderate" and "extreme" road-types suggests that whenever a fade is encountered which exceeds 5 dB, the physical characteristics of the trees which create the fades are the same. In other words, the different roads are distinguished by the frequency with which tree shadowing is encountered. Once encountered, the shadowing duration characteristics are similar.

Fade duration statistics have also been compiled by Goldhirsh and Vogel [1989] in central Maryland for angles of 30°, 45°, and 60° for 5 dB and 10 dB thresholds. A slight elevation angle dependence was discernible for the three cases; the smaller the elevation angle, the larger the fade duration for any fixed percentage. For example, the 30° fade duration showed approximately twice that for the 60° case. This is consistent with the fact that at the lower elevation angles there is generally more persistent shadowing.

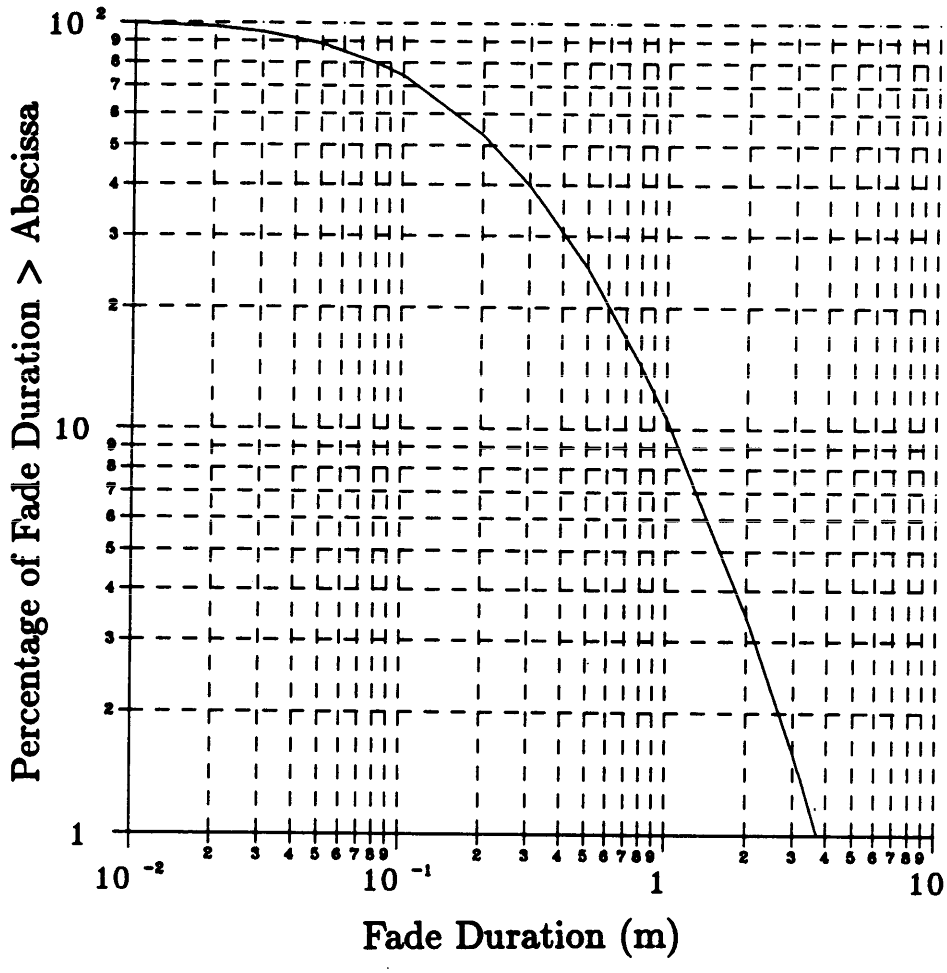

Figure 5.2: Best fit log-normal distribution (5.1) depicting fade durations for a 5 dB threshold. The distribution encompasses road types which exhibit "moderate" and "extreme" shadowing. The distribution is plotted on logarithmic scales for convenience.

Table 5.3: Non-fade duration regression values of β and γ satisfying the power expression (5.6) at a 5 dB threshold for road-types exhibiting "moderate" and "extreme" shadowing at a path elevation angle of 51°.

Shadowing Level	β	γ	% rms Deviation	Distance (km)
Moderate (Run 1)	20.54	0.58	33.3	33.0
Moderate (Run 2)	20.54	0.58	20.5	8.1
Extreme	11.71	0.8371	9.3	2.4

5.4 Cumulative Distributions of Non-Fade Durations

A "non-fade duration" event of distance duration dd is defined as the distance over which the fade levels are persistently smaller than a prescribed fade threshold. A non-fade duration analysis was performed by the authors employing the same data set as described above for the "fade duration" case. The measured data were noted to fit the power expression

$$\mathrm{P(NFD > dd \mid A < }A_q) = \beta(\mathrm{dd})^{-\gamma} \tag{5.6}$$

where $\mathrm{P(NFD > dd \mid A < A_q)}$ is the percentage probability that a continuous non-fade distance NFD exceeds the duration distance dd (m) given the condition that the fade is smaller than the threshold A_q. The values of the parameters β and γ in the formulation (5.6) are listed in Table 5.3 for road types exhibiting "moderate" and "extreme" shadowing assuming a 5 dB fade threshold. As noted, a single best fit power curve has been derived for the two "moderate" runs. In Figure 5.3 are plotted the best fit curves (5.6) for the indicated parameter values given in Table 5.3.

Employing an analogous expression to (5.2), the joint absolute probability of exceeding a non-fade duration distance dd for which the fade is smaller than A_q is given by,

$$\mathrm{P(NFD > dd, A < }A_q) = \mathrm{P(NFD > dd \mid A < }A_q)\,\mathrm{P(A <}A_q) \tag{5.7}$$

where the first right hand factor is given by (5.6) and the second is obtained from $1 - \mathrm{P(A >}A_q)$ from (5.3).

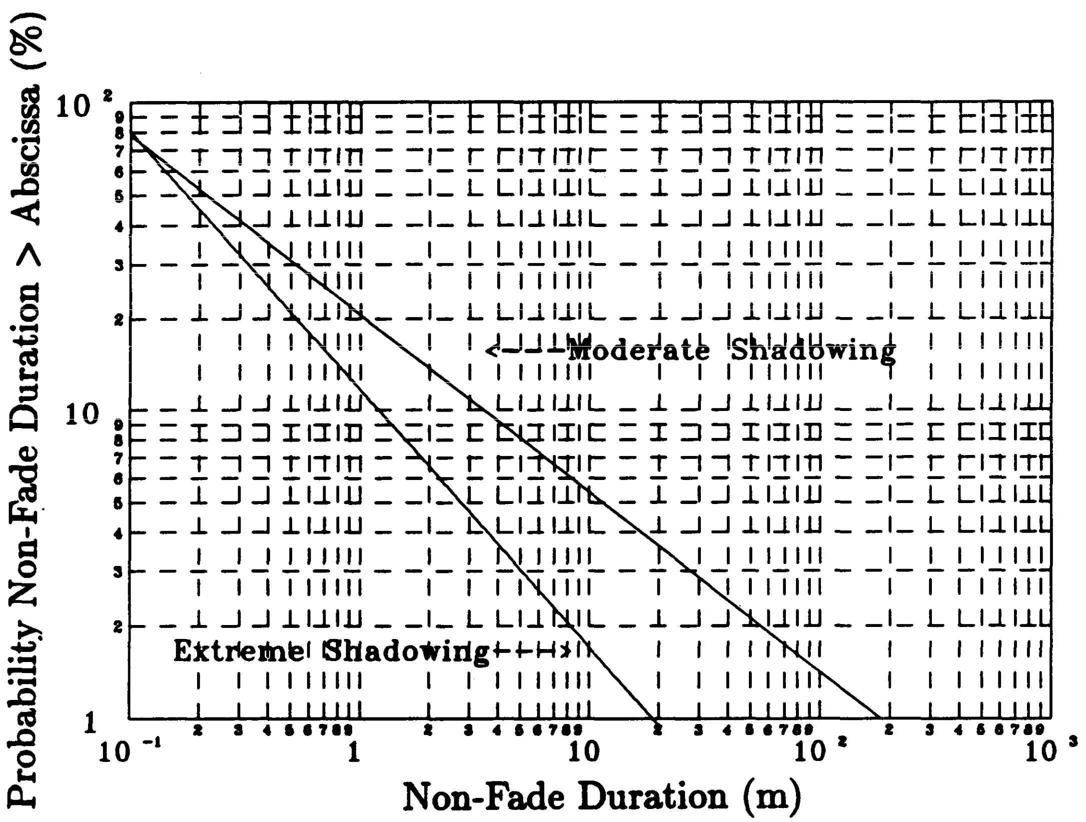

Figure 5.3: Best fit power curves (5.6) depicting non-fade durations for a 5 dB threshold for road types which exhibit "moderate" and "extreme" shadowing.

5.5 Cumulative Distributions of Phase Fluctuations

Phases were obtained from measured I and Q components after variations due to Doppler and oscillator drifts were eliminated using a high pass filter [Hase et al., 1991]. Conditional cumulative phase distributions were derived for each of the road-types described above. The conditions for these distributions were that the fades exceed attenuation thresholds levels ranging between 2-8 dB.

The "best fit" phase fluctuation distributions were found with good accuracy to follow a fifth order polynomial over a percentage exceedance range of 1% to 90% having the form

$$P(\phi > \phi_u | A > A_q) = \sum_{i=1}^{6} a_{i-1}\phi^{i-1} \tag{5.8}$$

where (5.8) may be read as the probability that the phase ϕ (degrees) exceeds the threshold level ϕ_u given a fade A(dB) exceeds the threshold level A_q. In Table 5.4 is given a listing of the values of the polynomial coefficients a_i at the threshold fade level of 5 dB for the "extreme" and "moderate" road types (Figure 5.1). The corresponding phase fluctuation distributions are given in Figure 5.4.

We note that over the range 5% to 95% in Figure 5.4, the phases are within $\pm 15°$ relative to the average for both the "moderate" and "extreme" cases. The indicated "best fit" polynomials agreed (in phase) with the individual measured distributions to within 15% rms.

For the "moderate" runs, cumulative distributions of phases over the probability range 1% to 90% were found to be minimally dependent on fade thresholds of 2 to 8 dB. We define the "phase spread" as the maximum phase difference (at equal probability) between the individual distributions for the different fade thresholds. A phase spread of less than 5° was noted for the "moderate" case over the range of distributions having fade thresholds 2 to 8 dB. For the "extreme" case, an approximate 20° phase spread (or less) was noted within the 1% and 99% levels over the fade threshold level of 2 to 8 dB.

Based on the above results, it would appear the influence of phase fluctuations on demodulation techniques at the elevation angle considered (e.g., 51°) is minimal and that LMSS channel characteristics can be estimated without considering phase. At lower elevation angles, greater multipath may be prevalent increasing the phase fluctuation spread. Loo

Table 5.4: Listing of polynomial coefficients characterizing phase fluctuation distributions of the form (5.8) for road types exhibiting "moderate" and "extreme" shadowing and a 5 dB fade threshold

Road Type	Polynomial Coefficients					
	a_o	a_1	a_2	a_3	a_4	a_5
Moderate	56.51	−6.516	-7.325×10^{-2}	2.380×10^{-2}	2.059×10^{-4}	-3.985×10^{-5}
Extreme	54.23	−4.242	-1.0897×10^{-2}	6.425×10^{-3}	2.082×10^{-5}	-4.258×10^{-6}

(private communication) reported large phase fluctuations for elevation angles between 5° and 20° which have a significant impact on digital communications.

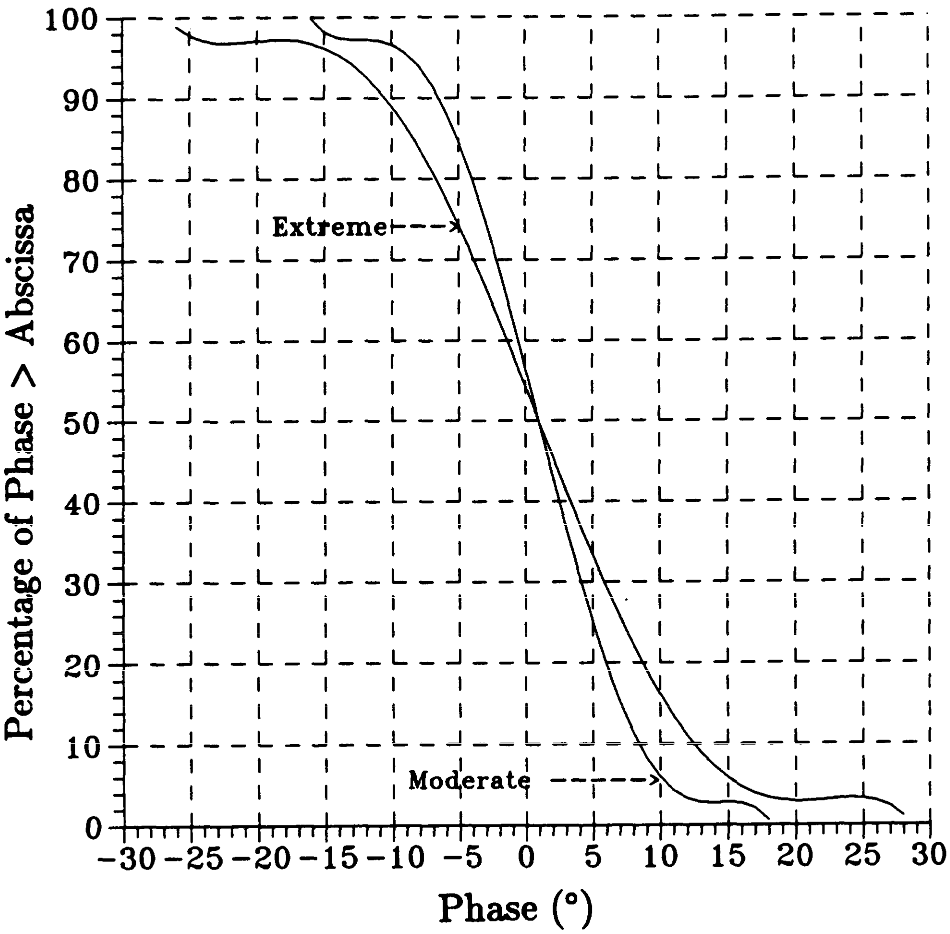

Figure 5.4: "Best polynomial fit" (5.8) cumulative phase distributions for road types which exhibit "moderate" and "extreme" shadowing for a 5 dB fade threshold.